Natural Recession of the Eastern Margin of the Leofnard Salt in Western Canada

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ABSTRACT

The Lloydminster area (T35-65, R15W3M-lOW4M) of east-central Alberta and west-central Saskatchewan, Canada, is dissected by the north-northwest trending updip active dissolution margin, of the Devonian Leofnard Member rock salt. West of this margin, up to 150 m of rock salt is preserved; updip and to the east, the salt has mostly been leached from the rock record. The margin is up to 40 km wide and characterized by extreme local variations in net salt thickness.

The dissolution of the Leofnard rock salt in the Lloydminster area has resulted in the entrapment of significant hydrocarbon accumulation. Stratigraphic traps, for example, have formed where reservoir facies were either preferentially deposited or preserved in salt-dissolution lows. Structural traps, in contrast, have formed where reservoir facies are draped across residual salt or collapse features. It has been estimated that three trillion barrels of oil (mostly of high viscosity and unrecoverable) are entrapped along the eastern dissolution margin of the Leofnard rock salt in western Canada.

A record of the westward progression of the dissolutional edge of the Leofnard salt is locked in the stratigraphic column. This progression is recorded as localized interval thickening in areas where dissolution and deposition were contemporaneous. The horizontal positioning of these interval thicks as a function of their geologic age provides a time record for the positioning of the salt edge.

To further explain the process of salt dissolution in the Lloydminster area, we present a suite of contour maps, geologic cross-sections, and seismic profiles. These data depict the present-day distribution of the Leofnard salt in the Lloydminster study area. They support the theses that: (1) the dissolution margin of the Leofnard rock salt originated along the Elk Point outcrop to the east of the study area during the pre-Cretaceous; and (2) the margin receded into the northeastern part of the Lloydminster study area during earliest Cretaceous or pre-Cretaceous time and migrated progressively thereafter into its current position. From the perspective of the explorationist, such information is important because it identifies prospective play areas with high potential for the formation of salt-related stratigraphic traps and/or structural traps.

INTRODUCTION

The Prairie Formation (upper Elk Point subgroup, Middle Devonian age; Figure 1) is an interbedded succession of halite, sylvite, bedded anhydrite, and minor dolostones that grade westward into shales. It is formally subdivided into a lower unit, the Whitkow Member, an upper unit, the Leofnard Member, and the intervening anhydritic Shell Lake Member (Baillie, 1953; Holter, 1969; Hamilton, 1971; Reinson and Wardlaw, 1972; Meijer Drees, 1986). The Leofnard Member as described in Meijer Drees (1986) is rock salt, being comprised of an interbedded succession of predominantly halite salt, anhydrite, and minor dolostone and shale.

Previous studies (Anderson, 1991; Anderson and Ceder-wall, 1993), using a large amount of well-log data and correlating the timing and location of salt-dissolution episodes with isopach thicks, report that Leofnard rock salt with a net thickness of 125-150 m was more-or-less uniformly deposited throughout the Lloydminster study area (T35-65, R15W3-lOW4). As a result of leaching, the present-day distribution of this rock salt has been significantly altered (Figures 2 and 3). The Lloydminster area is now dissected by the north-northwest trending eastern dissolution margin of the Leofnard Member rock salt. West and southwest of this margin, up to 150 m of rock salt is preserved; to the northeast (updip), the salt has mostly been leached from the rock record. Jackson (1984) estimates that

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three trillion barrels of oil are entrapped along the margin of the Leofnard salt; unfortunately most of this oil is highly viscous and unrecoverable with present technology.

The dissolution margin is up to 40 km wide in places and is characterized by extreme local variations in net salt thickness (Figure 3). Furthermore, there is evidence that dissolution along this margin is currently active. Horner and Hasegawa (1978) report that several epicenters in southern Saskatchewan overlie "a large multistage solution structure" and suggest cavity formation in the Prairie Evaporite as possibly providing the earthquake mechanism. They state that tensional faulting in caprock overlying a cavity is a much more likely mechanism than cavity collapse. Of all known events within the dissolution margin, the two that lie closest to our present study area occurred in 1984 and 1993 (D.J. Gendzwill, pers. comm.) at Redberry Lake in T43, R8W3M (cf. Figure 3b). These events had local magnitudes *(M_L)* of 2.3 and 2.6, respectively.

Horner et al. (1973) and Horner and Hasegawa (1978) attribute at least one event *(M_L* = 3.7) along the dissolution margin to strike-slip dislocation linked to a zone of basement weakness. This interpretation, supported by a partial focal-mechanism solution, is consistent with the idea that reactivation of such basement-linked faults may provide the fluid conduits that promote salt dissolution. A number of other earthquakes in Saskatchewan have been attributed to potash mining excavations (Gendzwill et al., 1982).

As noted in Vigrass (1977), Putnam (1982), Smith et al. (1984), Cederwall (1989), Anderson and Cederwall (1993), and

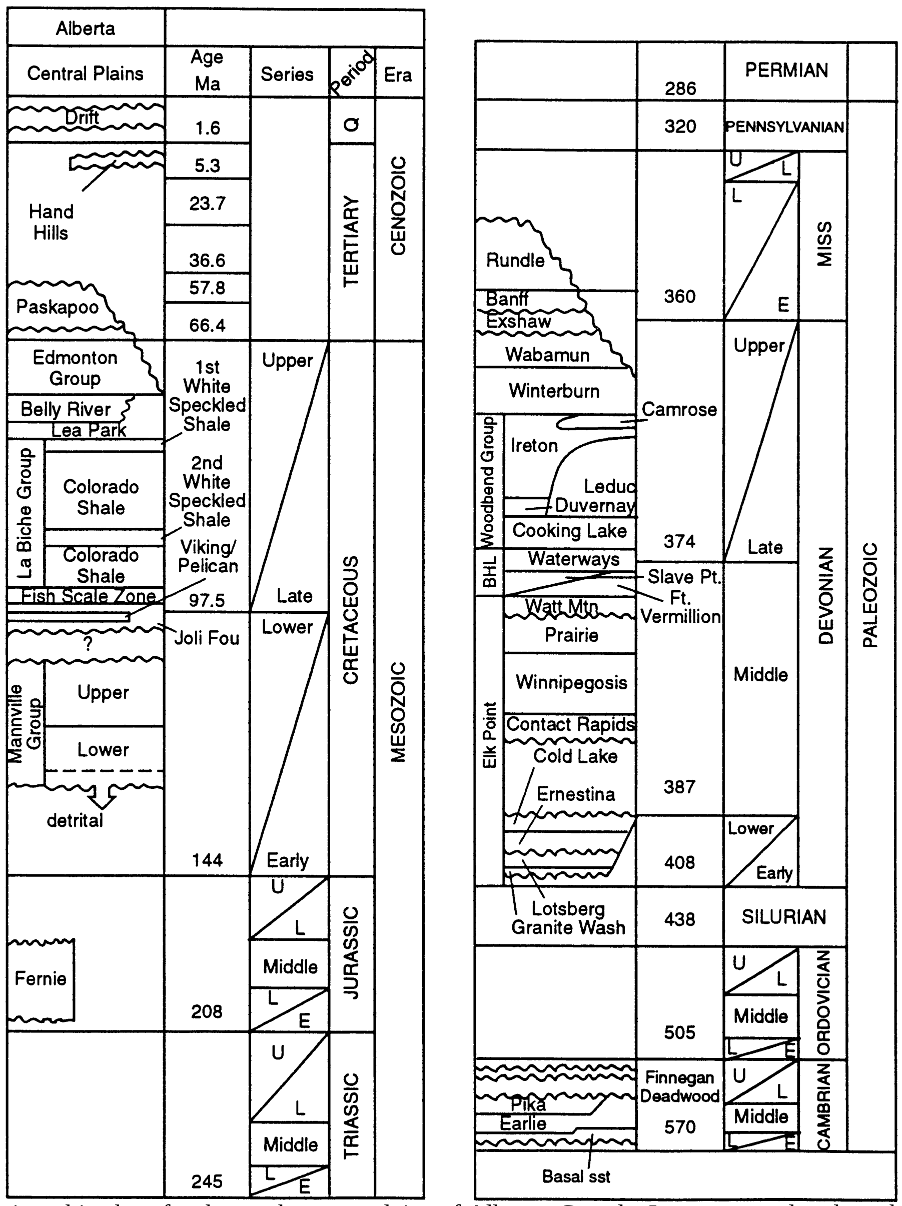

FIG. 1. Stratigraphic chart for the northeastern plains of Alberta, Canada. In east-central and southern Alberta, salts are present in at least six Devonian stratigraphic intervals, including the Lotsberg, Cold Lake, Prairie, Beaverhill Lake (BHL), Leduc, and Wabamun formations. The Leofnard Member is the upper rock-salt unit of the Prairie Formation. Pre-Albian is X13 Ma BP; post-Santonian is <84 Ma BP.

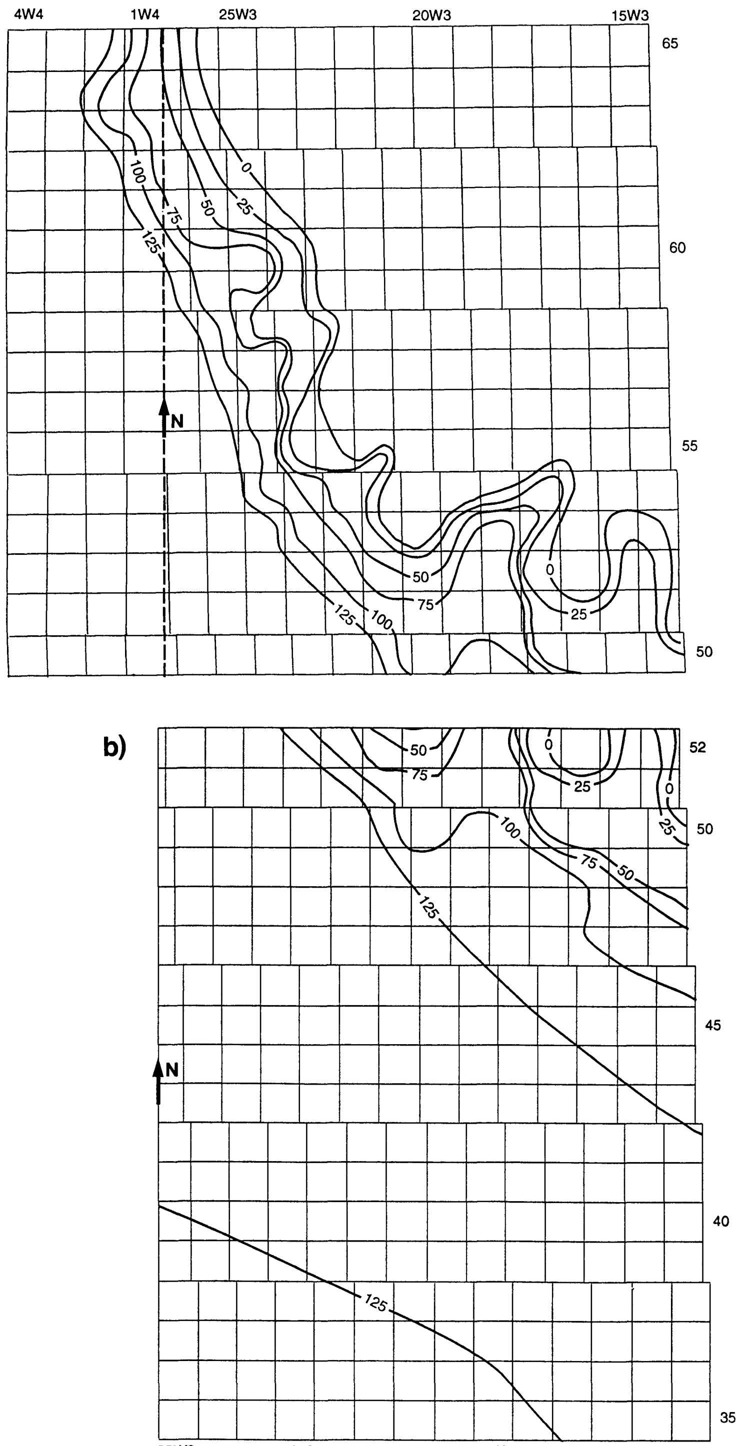

Fig. 2. Contour map (in meters) of (a) the northern part of the Lloydminster study area, from T50 to T65, and (b) the southern part of the area, from T35 to T52, showing our interpretation of the distribution of the Leofnard salt at the end of Mannville time (mid-Cretaceous). Except for the extreme southwestern part of this area (south of T40 and west of R20), 125 to 150 m of Leofnard rock salt was more-or-less uniformly deposited throughout the study area.

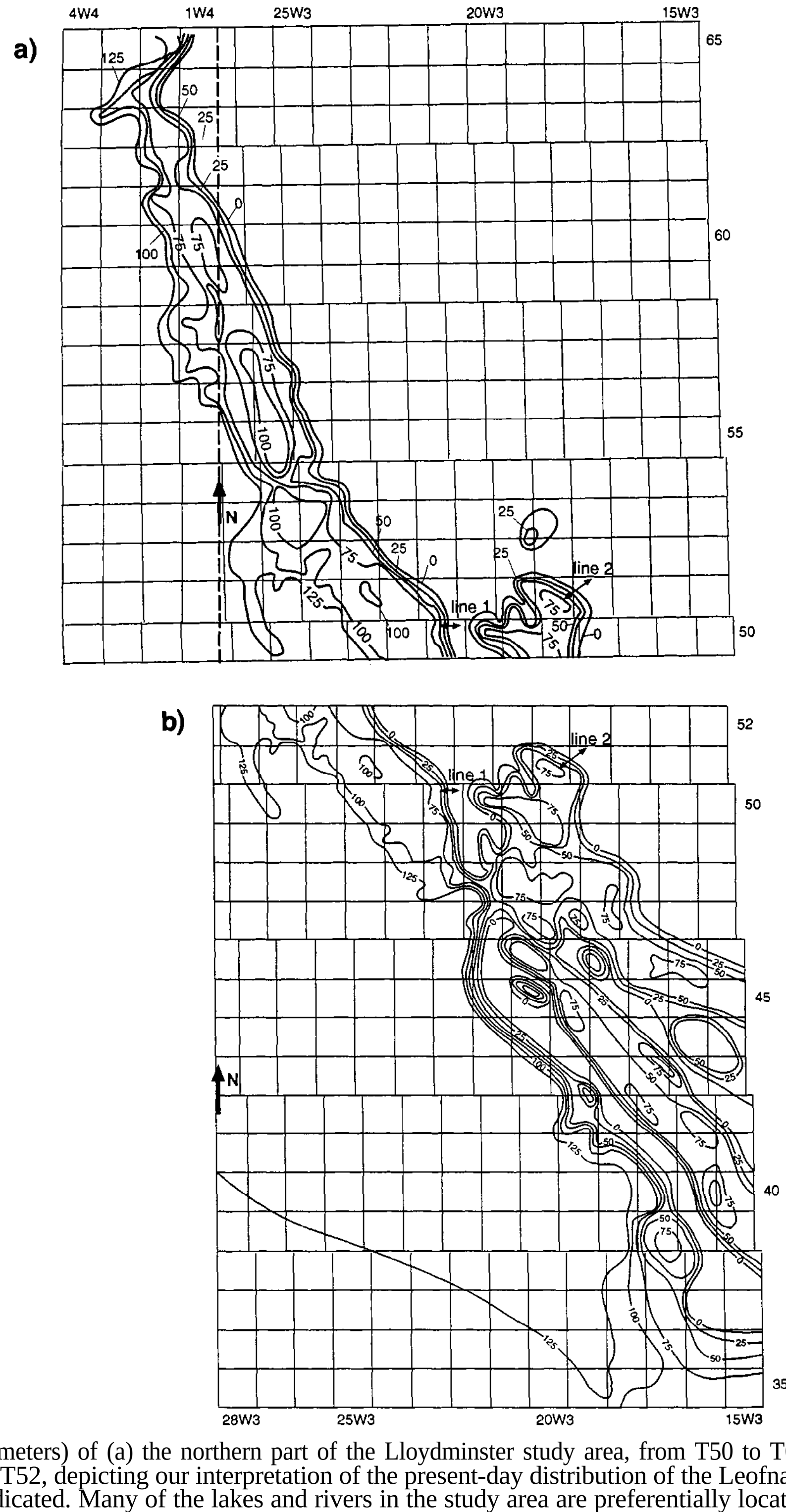

FIG. 3. Contour map (in meters) of (a) the northern part of the Lloydminster study area, from T50 to T65, and (b) the southern part of the area, from T35 to T52, depicting our interpretation of the present-day distribution of the Leofnard salt. The locations of the two seismic lines are indicated. Many of the lakes and rivers in the study area are preferentially located along the salt-dissolution margin, suggesting that significant leaching has occurred in post-glacial time.

others in their discussions of the petroleum geology of the Lloydminster area, the dissolution of the Leofnard salt is important to oil and gas explorationists for several reasons: (1) stratigraphic traps form where reservoir facies were either preferentially deposited or preserved in salt-dissolution lows; (2) reservoir facies develop in high-energy environments such as topographic highs that are controlled by salt edges or remnants; (3) structural traps form where reservoir facies are draped across salt remnants or collapse features; and (4) residual salt can be misinterpreted as reefs, faults, or other structural features (Anderson et al., 1988; Anderson and Brown, 1992b).

DISSOLUTION OF THE LEOFNARD SALT

The Leofnard salt in the Lloydminster study area was relatively stable until the pre-Cretaceous. This is evidenced by the uniformity of the Paleozoic units that overly it. The thicknesses of the Paleozoic units vary only slightly and uniformly apparently as a result of regional dip (Figure 4). Uplift and erosion at that time exposed the encompassing Elk Point Group to a near-surface environment some 40 km to the northeast of the study area and initiated salt dissolution along a more-or-less continuous front that effectively paralleled the Elk Point outcrop (Anderson and Cederwall, 1993; Anderson and Knapp, 1993). This dissolution margin migrated westward (basinward) relatively rapidly across the northeastern part of the Lloydminster study area during earliest Cretaceous and pre-Cretaceous time (Figures 2 and 3). This initial phase of leaching was probably analogous to the dissolution of shallow, bedded Permian rock salts in Kansas during the Quaternary (Anderson et al., 1994). The rates of dissolution and migration after the onset of Cretaceous sedimentation were relatively slow and variable, being affected by processes such as the influx of meteoric water through the Elk Point outcrop/subcrop, the centrifugal flow (i.e., from basin interior to the margins) of interstitial waters, rock salt creep, regional faulting and/or fracturing, glacial loading and unloading, and the partial dissolution of rock salts within the underlying Lower Elk Point Subgroup (Anderson and Brown, 1992a, b; Anderson and Knapp, 1993). Figure 3 depicts the present-day distribution of the Leofnard salt in the Lloydminster area.

Figure 4 is a southwest-northeast oriented geologic profile depicting the dissolution margin of the Leofnard rock salt. (Note: the fact that only a few wells were incorporated into the

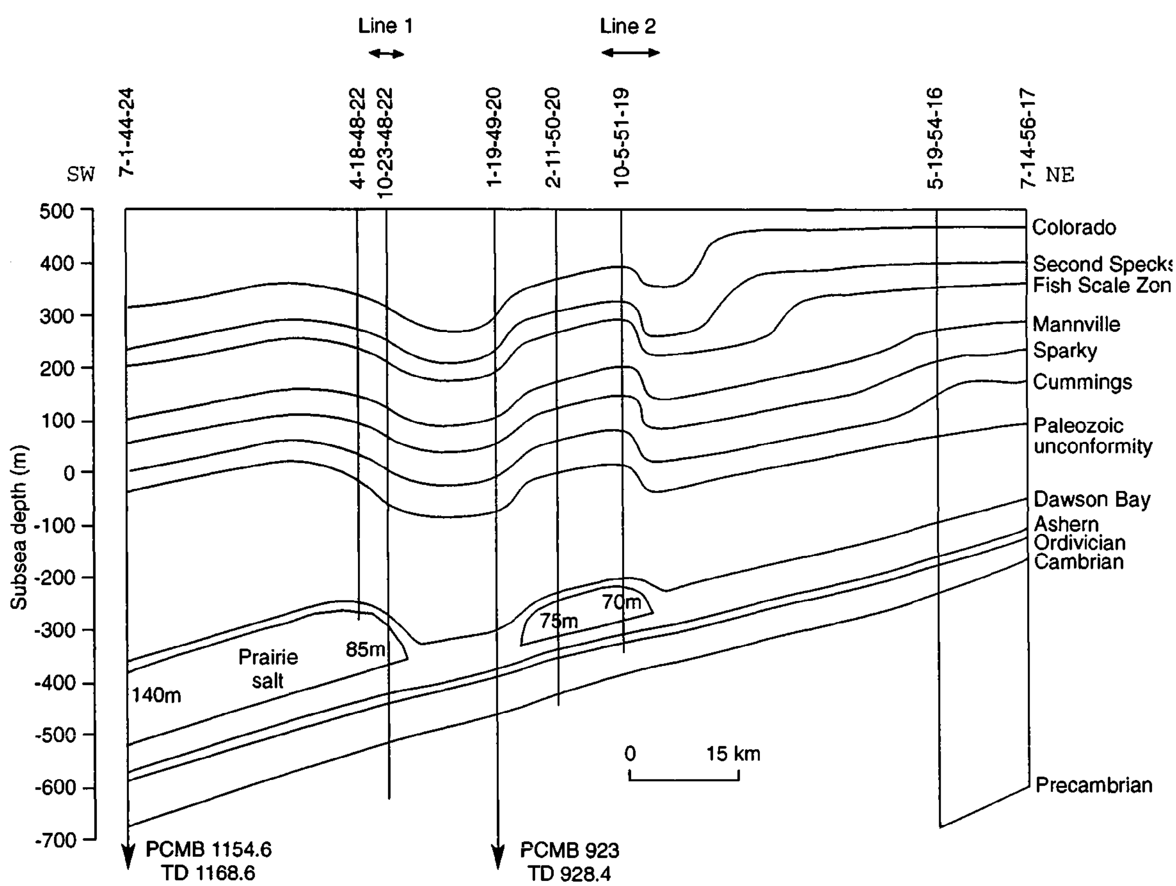

FIG. 4. Southwest-to-northeast geologic profile illustrating the structural relationships between the residual Leofnard (Prairie) rock salt and the post-salt strata. The relative lack of control is indicative of the paucity of wells to the east of the present-day active salt margin. Dissolution at the 7-14 and 5-19 well sites is interpreted as pre-Albian in origin and is attributed to the rapid westward recession of the main salt front during the pre-Cretaceous and earliest Cretaceous. To the southwest of 5-19, leaching occurred progressively later and in association with the continued recession of the salt margin. Dissolution at the 10-5, 2-11, 1-19, l0-23 and 4-18 locations is predominantly post-Santonian in origin. Representative locations of the two seismic lines are indicated.

cross-section reflects the relative paucity of deep control in the area.) The post-salt strata have been interpretively correlated in order to illustrate the interrelationships between salt dissolution, subsidence, and contemporaneous sedimentation in the study area. Dissolution at the 7-14 and 5-19 well sites is interpreted as pre-Albian in origin and is attributed to the rapid westward recession of the salt margin during the pre-Cretaceous and earliest Cretaceous. To the southwest of well 5-19, leaching occurred at progressively later times and in association with the continued westward recession of the salt margin. Dissolution at the l0-5,2-ll, l-19,10-23, and 4-18 well locations is predominantly post-Santonian in origin. This geologic profile is consistent with the present-day and reconstructed salt distribution maps presented as Figures 2 and 3.

Detailed cross-sections similar to that of Figure 4 are an exploration prerequisite in areas of salt dissolution. The interpretation of such cross-sections can be used to identify play fairways (areas where prospective reservoir facies are structurally closed and areas where prospective reservoir facies were preferentially deposited). As illustrated below, seismic data can provide control in inter-well areas and at subwell depths.

SEISMIC DATA

In support of the Leofnard net salt distribution maps (Figures 2 and 3), the geologic profile of Figure 4, and our postulated processes of salt dissolution, we present two interpreted seismic lines (Figures 5 and 6, and 7 and 8). Line 1 crosses the outer margin of the Leofnard salt in T50, R22W3M (Figure 3) and is representative of the geologic profile from well l0-23 to 1-19 inclusive (Figure 4). Line 2 crosses the outer margin of the Leofnard salt in T51, R19W3M (Figure 3) and is representative of the geologic profile at, and several kilometers to the northwest of, well 10-5. The reflections on these seismic profiles were identified and correlated with the aid of several models, including the 6-5-51-2OW3M l-D, normal-polarity, synthetic seismogram of Figure 9.

In the study area: (1) the Prairie Formation, where present, overlies the Winnipegosis Formation; (2) the base of the Fish Scale Zone represents the Upper Cretaceous/Lower Cretaceous boundary; (3) the Beaverhill Lake Group is the Paleozoic (sub-Cretaceous) unconformity; and (4) the Cambrian is the sub-Ordovician unconformity (Figure 1).

On the normal-polarity seismic Lines 1 and 2 (Figures 5 and 6, and 7 and 8) several interesting relationships are observed and/or interpreted:

1) The Prairie event (trough) represents the reflection from the top of the residual Leofnard salt (salt/shale contact). Where Leofnard rock salt is preserved, the event (peak) labeled Winnipegosis corresponds to the base of the salt (salt/anhydrite contact). In those areas where the salt has been leached totally, the Winnipegosis event corresponds to the top of the residual anhydrite (shale/anhydrite contact). Trace 80 is interpreted as the near-zero edge of the remnant rock salt on Line 1 (Figures 5 and 6). Trace 327 is interpreted as the near-zero edge of the remnant rock salt on Line 2 (Figures 7 and 8). Again, Line 1 crosses the margin of the Leofnard salt in T50, R22W3M (Figure 3) and is representative of the geologic profile from well l0-23 to 1-19 inclusive. Up to 65 m (30 ms) of rock salt is preserved at the western end of this seismic profile. Line 2 crosses the margin of the Leofnard salt in T51, R19W3M (Figure 3) and is representative of the geologic profile at and several kilometers to the northwest of well 10-5. Up to 85 m (40 ms) of rock salt is preserved at the western end of this seismic profile.

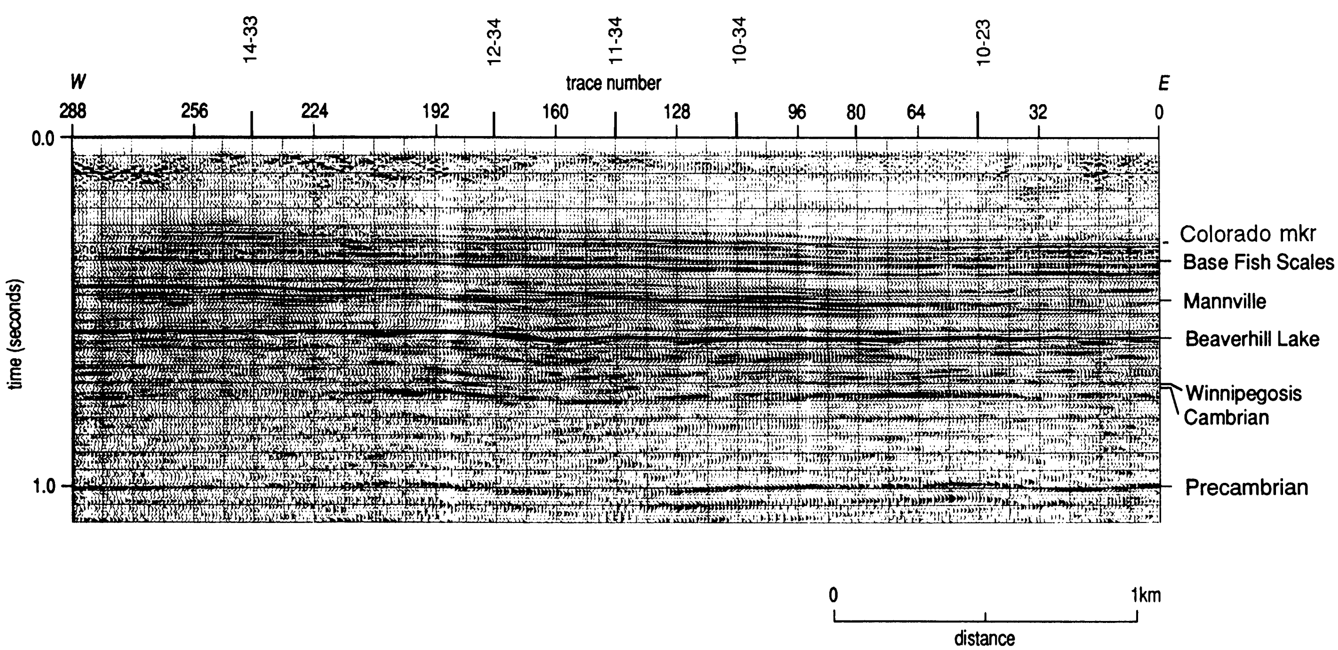

FIG. 5. Seismic Line 1. This 24-fold normal-polarity seismic line was acquired using a P-shooter energy source. This west-to-east profile is about 3.5 km long, crosses the outer margin of the Leofnard salt in T50, R22W4M, and is representative of the geologic profile from l0-23 to 1-19, inclusive (Figure 4).

2) The Beaverhill Lake/Winnipegosis and the Beaverhill Lake/Cambrian intervals thin from west to east on both seismic lines. On Line 1, these intervals thin by about 30 ms between traces 288 and 80 and are relatively constant to the east, indicating that about 65 m of salt is preserved near the western end of the seismic line and that trace 80 is a near-zero edge of the rock salt (Figure 4). On Line 2, these intervals thin by about 40 ms between traces 373 and 321 and are relatively constant to the east, indicating that about 85 m of salt is preserved near the western end of the seismic line and that trace 327 is a near-zero edge of the rock salt (Figure 4).
3) Time-structural relief at the Beaverhill Lake level varies across the seismic sections. On Line 1 (Figures 5 and 6), this event is dip-reversed locally, being up to 30 ms (possibly as much as 50 m) lower at trace 0 than at trace

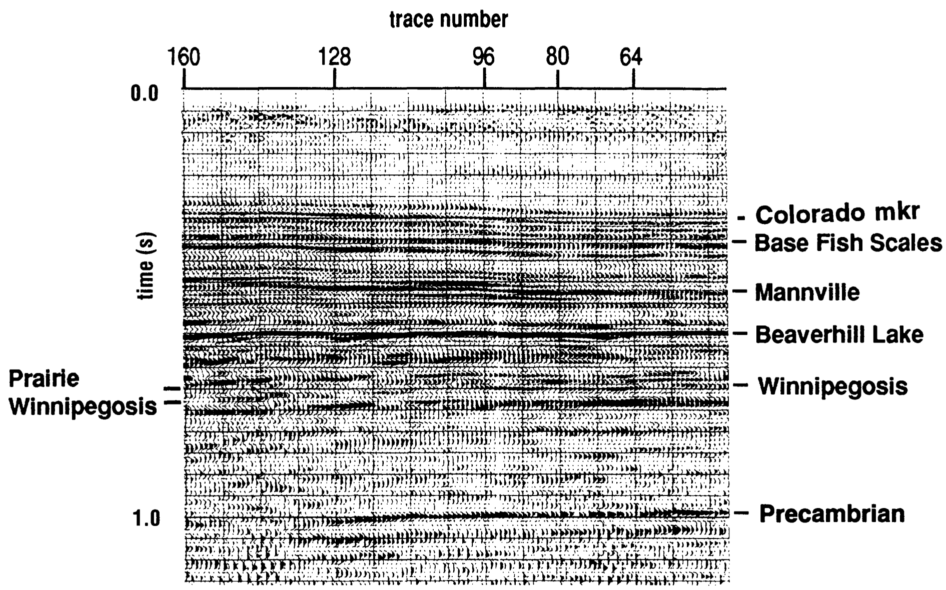

FIG. 6. Enlargement of a portion of seismic Line 1 (Figure 5). The seismic line crosses the near-zero edge of the Prairie salt in the vicinity of trace 80. The Prairie/Winnipegosis interval (west of trace 80) represents the salt interval.

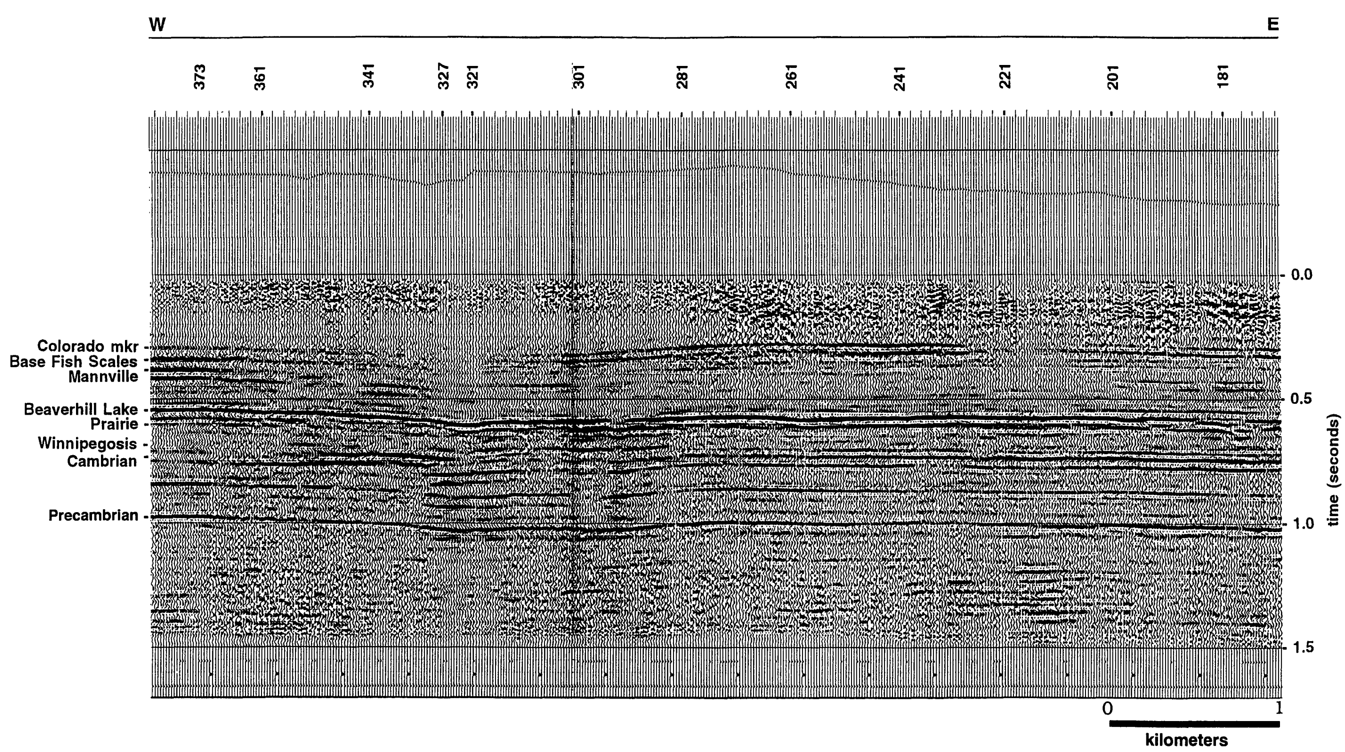

FIG. 7. Seismic Line 2. This 12-fold normal-polarity seismic line was acquired using a dynamite source. This WSW-ENE profile is about 6.5 km long, crosses the outer margin of the Leofnard salt in T51, R19W3M, and is representative of the geologic profile at and several kilometers to the northwest of well 10-5 (Figure 4).

288. Relative to the regional trend (of about 4 m/km), this time-structural relief is consistent with the 65 m estimate for the thickening of the Leofnard salt along the entire length of the seismic line and supports our thesis that significant salt dissolution occurred in this area in post-Paleozoic time. On Line 2 (Figures 7 and 8), the Beaverhill event is up to 55 ms (possibly as much as 70 m) lower at trace 181 than at trace 373, again supporting the 85 m estimate for the thickening of the Leofnard salt along the entire length of the seismic line. These data are consistent with our interpretation that 125-150 m of rock salt was deposited in the vicinities of the seismic profiles and that these salts were leached after the onset of Cretaceous sedimentation.

4) On Line 1, the Mannville, base Fish Scales, and Colorado events are effectively parallel and locally dip-reversed, being about 50 ms (possibly as much as 65 m) lower at trace 0 than at trace 288. This pattern of time-structural relief is consistent with the 65 m estimate for the thickening of the Leofnard salt along the entire length of the seismic profile and with the thesis that salt dissolution in the vicinity of wells 10-5, 2-11, 1-19, 10-23, and 4-18 was predominantly post-Santonian in origin. (If the dissolution margin had migrated along the length of seismic Line 1 prior to the end of the Santonian, it is unlikely that the Colorado, base Fish Scales, and Mannville events would be time-structurally parallel).

5) On Line 2 the Mannville, base Fish Scales, and Colorado events are locally dip-reversed but not parallel. The Mannville event is about 45 ms (possibly as much as 60 m) lower at trace 181 than at trace 371; the base Fish Scales event is about 30 ms (possibly as much as 40 m) lower at trace 181 than at trace 371; and time-structural relief at the Colorado event is effectively the same at traces 181 and 371. This pattern of time-structural relief is consistent with the thesis that the dissolution margin of the Leofnard salt migrated from east to west along the seismic profile during the Cretaceous (Figure 4).

6) On Line 2 the Mannville/Beaverhill Lake interval is consistently about 10 ms thicker towards the eastern end of the seismic line (in contrast to the regional trend of depositional thinning to the east). Similarly, the base Fish Scales/Mannville and Colorado/base Fish Scales intervals are consistently l0-15 ms and 30-40 ms thicker, respec-

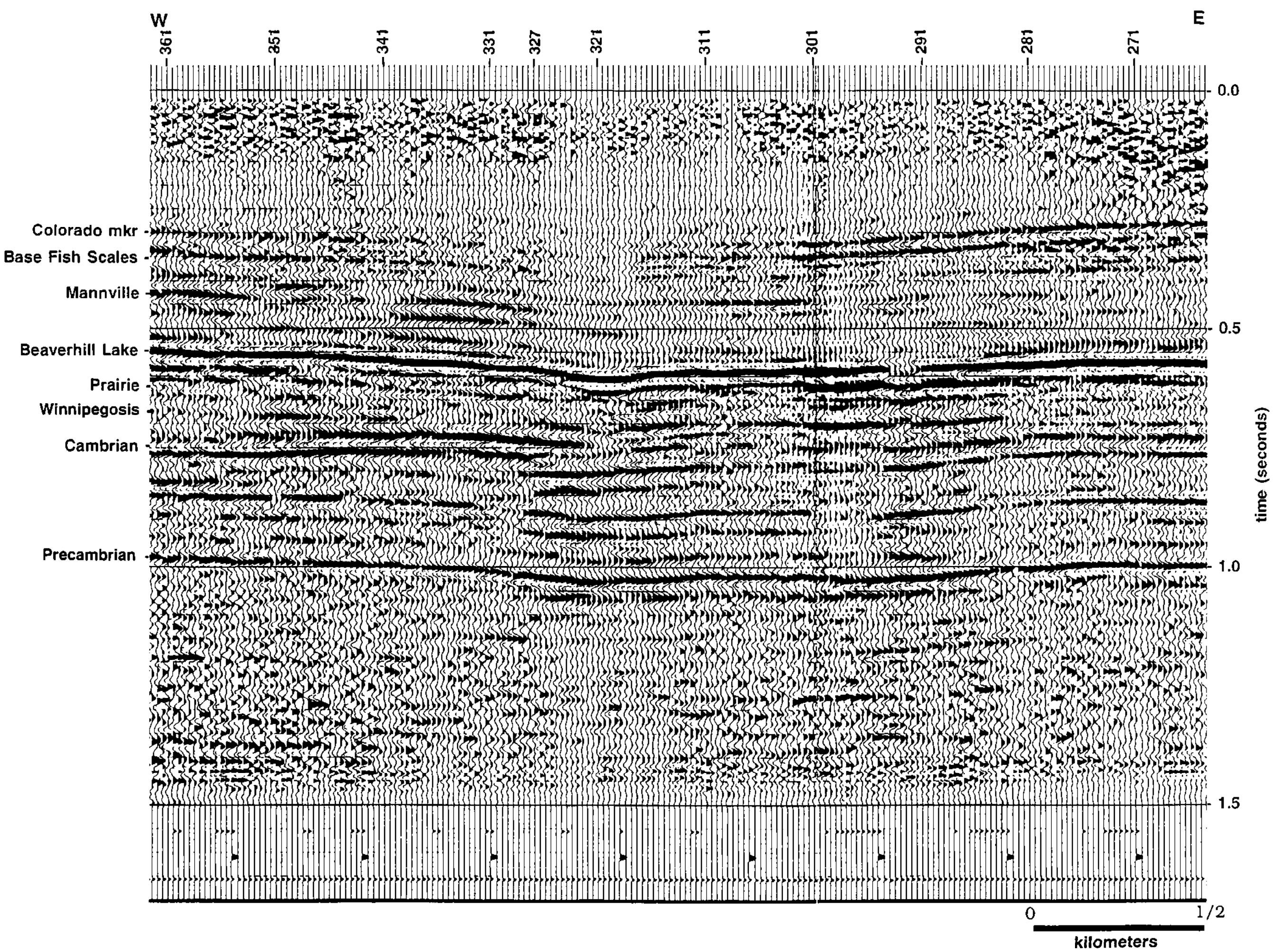

FIG. 8. Enlargement of a portion of seismic Line 2 (Figure 7). The seismic line crosses the near-zero edge of the Prairie salt in the vicinity of trace 327.

tively, across the eastern half of the seismic line. These observations are consistent with the thesis that the dissolution margin of the Leofnard salt progressively receded in a westerly direction along the seismic profile during the Cretaceous (Figure 4).

7) On Line 2 (Figures 6 and 7), the post-Colorado interval is anomalously thick (by up to 60 ms) between traces 291 and 327. This anomalous thickening is attributed to post-Santonian salt dissolution. The time-structural relief (up to 30 ms) at the Winnipegosis level between traces 291 and 327, is interpreted as velocity "push-down" and is attributed to the recent (Quaternary) dissolution of up to 60 m of rock salt. This latest phase of leaching would have resulted in the deposition of an equivalent thickness of low-velocity (on the order of 1500 m/s) unconsolidated sediment.

8) On Line 1 (Figures 7 and 8), the Lower Cretaceous and Paleozoic reflections between traces 80 and 168 are interpreted to be similarly "pushed down" (by up to 15 ms). This push-down is thought to mask the true extent to which these post-salt strata are dip-reversed across the updip eastern dissolution edge of the Prairie Formation. Our preferred explanation is that these anomalies are velocity-variation effects related to salt

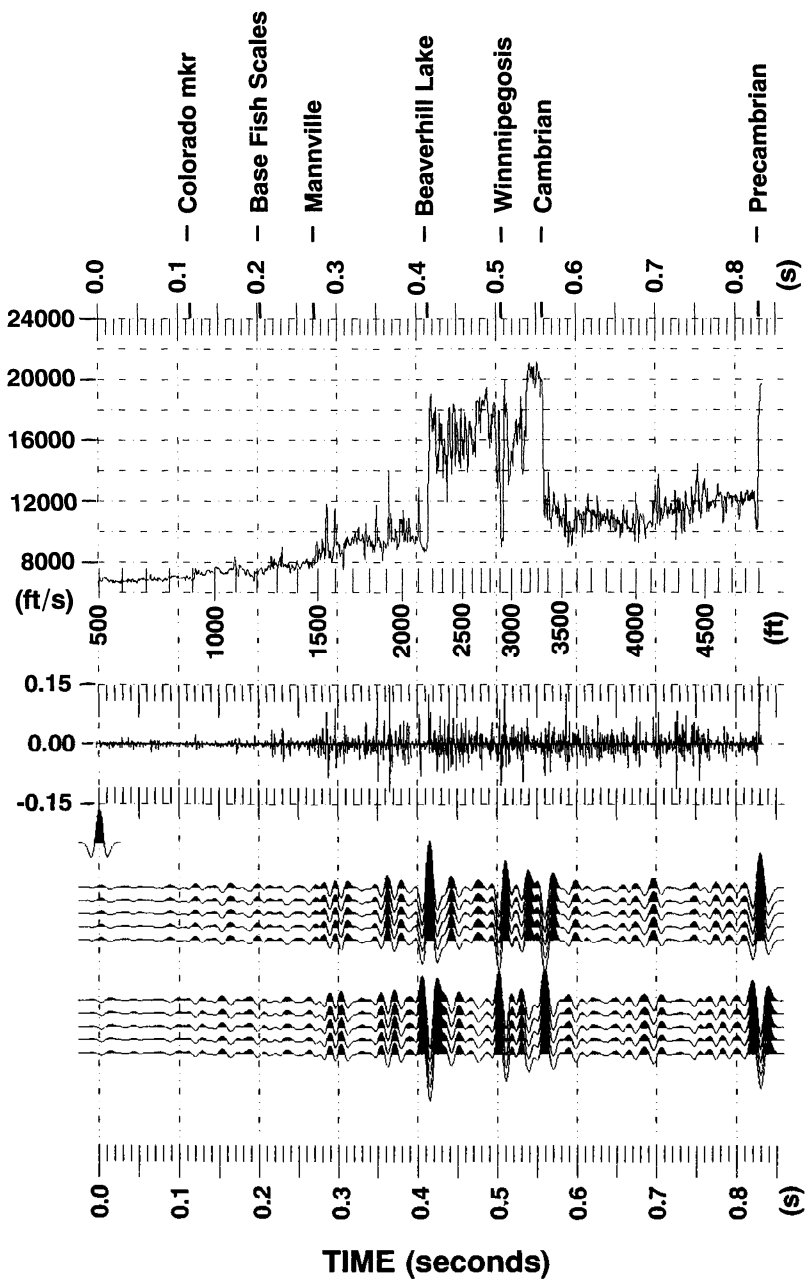

FIG. 9. Velocity log (top); reflectivity log; a zero-phase, 20-ms, 39-Hz Ricker wavelet; and normal- and reverse-polarity (bottom) synthetic seismograms for the 6-5-51-2OW3M well generated using this Ricker wavelet. This well did not encounter any residual Leofnard rock salt.

dissolution during the Quaternary. This latest phase of dissolution could have been caused by glacial processes (Anderson and Knapp, 1993).

The seismic data support the concept that the 125-150 m of Leofnard salt initially deposited in the Lloydminster study area remained relatively stable until the pre-Cretaceous. At this time and thereafter, the salt-dissolution margin, formed along the Elk Point outcrop some 40 km to the northeast, progressively migrated through the eastern part of the study area. With respect to the geologic profile (Figure 4), the seismic data support the interpretation that: (1) dissolution at the 7-14 and 5-19 well sites is interpreted as pre-Albian in origin; (2) southwest of 5-19, leaching occurred progressively later and in association with the continued recession of the salt margin; and (3) dissolution at the l0-5,2-11, 1-19, l0-23 and 4-18 locations is predominantly post-Santonian in origin.

CONCLUSIONS

The timing and the extent of the dissolution of the Leofnard salts is of interest to explorationist, for several reasons: (1) stratigraphic traps can form where reservoir facies were either preferentially deposited or preserved in salt-dissolution lows; (2) reservoir facies can develop in high-energy environments such as topographic highs that are controlled by salt edges or remnants; (3) structural traps can form where reservoir facies are draped across salt remnants or collapse features; and (4) salt remnants can be misinterpreted as reefs, faults, or other structural features.

As illustrated by the example data, the timing and the extent of salt dissolution in the Lloydminster area can be interpreted on the basis of seismic and well-log data. From the perspective of the explorationist this is important because it allows for the identification of prospective play areas with high potential for the formation of salt-related stratigraphic traps and/or structural traps. Present-day structural traps in the Lloydminster area are very young in age; thus migration of hydrocarbons into these traps is quite recent.

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